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DEVELOPMENT AND APPLICATIONS OF A MULTI-LEVEL STRAIN ENERGY METHOD FOR DETECTING FINITE ELEMENT MODELING ERRORS

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FOREWORD

McDonnell Douglas Helicopter Company (MDHC) has been conducting a study of finite element modeling of helicopter airframes to predict vibration. This work is being performed under U.S. Government Contract NAS1-17498. The contract is monitored by the NASA Langley Research Center, Structures Directorate.

This report presents the results of an effort spent on the development and application of a computational procedure for detecting modeling errors during the development of finite element models. Key NASA and MDHC personnel are listed below:

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1.0 INTRODUCTION

INTRODUCTION

The NASA Langley Research Center is sponsoring a rotorcraft structural dynamics program with the overall objective to establish in the United States a superior capability to utilize finite element analysis models for calculations to support industrial design of helicopter airframe structures. Viewed as a whole, the program is planned to include efforts by NASA, Universities, and the U.S. Helicopter Industry. In the initial phase of the program, teams from major manufacturers of helicopter airframes will apply extant finite element analysis methods to calculate static internal loads and vibrations of helicopter airframes of both metal and composite construction, conduct laboratory measurements of the structural behavior of these airframes, and perform correlations between analysis and measurements to build up a basis upon which to evaluate the results of the applications. To maintain the necessary scientific observation and control, emphasis throughout these activities will be on advance planning, documentation of methods and procedures, and thorough discussion of results and experiences, all with industry wide critique to allow maximum technology transfer between companies. The finite element models formed in this phase will then serve as the basis for the development, application, and evaluation of both improved modeling techniques and advanced analytical and computational techniques, all aimed at strengthening and enhancing the technology base which supports industrial design of helicopter airframe structures. Here again, procedures for mutual critique have been established, and these procedures call for a thorough discussion among the program participants of each method prior to the applications and of the results and experiences after the applications. The aformentioned rotorcraft structural dynamics program has been given the acronym DAMVIBS (Design Analysis Methods for VIBrationS).

As a major helicopter manufacturer, McDonnell Douglas Helicopter Company is participating in this program. As a part of this effort, this report presents the work done on development and application of a computational procedure which can be used to help the analyst to rapidly identify modeling errors during the development of finite element models. This procedure, which is a DMAP alter sequence written for MSC/NASTRAN, was applied to both the dynamic finite element model of the AH-64A Attack Helicopter and a customer-supplied model.

2.0 NASTRAN MODEL CHECKOUT TOOLS AT MDHC

NASTRAN DMAP CAPABILITIES

One of the main tools which has been used for modeling and analysis of airframe type structures at the McDonnell Douglas Helicopter Company is MSC/NASTRAN. Consequently, the model checkout techniques which have been developed here at MDHC, including the Multi-Level Strain Energy Check which is the subject of this report, have all been tailored for use with this program.

As a part of these efforts, the MSC/NASTRAN Direct Matrix Abstraction Programming (DMAP) capability, which is one of the main features of this finite element code, is used to alter the rigid format solution sequences and develop these model checkout tools. Consequently, a series of computational procedures have been developed which are currently being used at the McDonnell Douglas Helicopter Company and which have been found to be very useful in checking out finite element models at different stages of the modeling process.

NASTRAN DMAP CAPABILITIES

- NASTRAN IS USED AS A MODELING TOOL
- DMAP CAPABILITIES USED TO:
  - ALTER THE RIGID FORMATS
  - DEVELOP ADDITIONAL MODEL CHECKOUT TOOLS

NASTRAN MODEL CHECKOUT TOOLS AT MDHC

In conjunction with using MSC/NASTRAN, the model verification process is accomplished through a series of computational procedures which are introduced in the form of DMAP alters to a rigid format. During the use of these procedures, sufficient diagnostics can be obtained about both the global state and local areas of the finite element model. These procedures include: the Connection Check, the 1g Static Check, the Enforced Displacement Check,the Cholesky Decomposition Check, and the Multi-Level Strain Energy Check. It is the Multi-Level Strain Energy Check and its application to two models which is the subject of this report. However, for the sake of completeness, a brief summary of the capabilities of the other model checkout techniques will be presented first.

NASTRAN MODEL CHECKOUT TOOLS AT MDHC

- CONNECTION CHECK
- 1g STATIC CHECK
- ENFORCED DISPLACEMENT CHECK
- CHOLESKY DECOMPOSITION CHECK
- MULTI-LEVEL STRAIN ENERGY CHECK

CONNECTION CHECK

MSC/NASTRAN contains a series of rigid formats which dictate the procedures used in solving different types of problems. In each of these procedures the program executes a series of operations in order to assemble the structural matrices. Based on the information supplied for the grid point locations, the types of elements used to connect the grid points, the properties associated with each element, and the type of boundary conditions, the program assembles the structural matrices. It is during this assembly process that the program internally checks the validity of the connectivity relations among the specified structural elements and provides some information by printing out a Grid Point Singularity Table. However, there are instances where this table does not provide sufficient diagnostics and other means of problem identification are needed. The usual alternative in this case is to visually examine the model. While this often results in locating some of the errors, it is not a practically useful way to proceed if the model is large.

CONNECTION CHECK

- **INTERNAL CHECK OF ELEMENTS CONNECTIVITY (GRID POINT SINGULARITY TABLE)**
- **VISUAL EXAMINATION OF THE MODEL**
- **RIGID FORMAT ALTER NOT REQUIRED**

1g STATIC CHECK

For this check, either the assembled structure or an individual component is statically constrained to prevent motion as a rigid body, and a gravity loading is imposed. A static solution is used to calculate both the forces of constraint and the deflections which in turn are used to determine any modeling problems.

1g STATIC CHECK

- APPLICABLE TO EITHER INDIVIDUAL OR OVERALL STRUCTURAL MODEL
- APPLIED TO CONSTRAINED MODEL
- GRAVITY LOADING APPLIED IN A STATIC RUN
- FORCES OF CONSTRAINT AND DEFLECTIONS ARE USED TO LOCATE THE PROBLEM
- RIGID FORMAT ALTER NOT REQUIRED

ENFORCED DISPLACEMENT CHECK

This check identifies any overconstrained locations in the structure. For this purpose, the free-free model is subjected to static unit displacements in all six directions separately and the resulting strain energy values of all the elements in the structure are examined. A large value of strain energy is indicative of an overconstraint for that element and its associated degrees-of-freedom (DOF). It should be pointed out that this check does not provide any information about the state of the model at the G-set and N-set levels of model assembly.

ENFORCED DISPLACEMENT CHECK

- APPLICABLE TO EITHER INDIVIDUAL OR OVERALL STRUCTURAL MODEL
- APPLIED TO UNCONSTRAINED MODEL
- SEPARATE APPLICATIONS OF UNIT DISPLACEMENTS IN ALL SIX DIRECTIONS
- LARGE VALUES OF STRAIN ENERGY ARE INDICATIVE OF OVERCONSTRAINTS
- DOES NOT IDENTIFY THE PROBLEM AT G-SET OR N-SET LEVELS
- RIGID FORMAT ALTER NOT REQUIRED

CHOLESKY DECOMPOSITION CHECK

The purpose of this check is to identify singularities or mechanisms as well as near singularities or soft spots in the model at the F-set level. For this purpose, a DMAP alter is used which employs the DCOMP functional module to perform a triangular decomposition of the F-set stiffness matrix in the static solution sequence. Subsequent to this decomposition, a diagonal matrix results whose elements provide information about the conditioning of the stiffness matrix. A max factor diagonal value (i.e., ratio of the largest diagonal term to the lowest diagonal term) of over 10^5 indicates a soft spot (i.e., near singularity) while a value over 10^{10} is indicative of a mechanism (i.e., singularity). In addition to the max factor ratio, another parameter, ϵ, is calculated. Aside from round-off errors, any large nonzero value of ϵ is indicative of a singularity in the stiffness matrix.

CHOLESKY DECOMPOSITION CHECK

- IDENTIFIES SINGULARITIES (MECHANISMS)
- IDENTIFIES NEAR-SINGULARITIES (SOFT SPOTS)
- APPLIED TO UNCONSTRAINED MODEL
- DOES NOT IDENTIFY THE PROBLEM AT THE G-SET OR N-SET LEVELS
- RIGID FORMAT ALTER IS REQUIRED

3.0 MULTI-LEVEL STRAIN ENERGY CHECK

MULTI-LEVEL STRAIN ENERGY CHECK

In contrast to the usual model checkout techniques which were reviewed above, the Multi-Level Strain Energy Check is the only check which provides information about modeling problems at all three levels (i.e., G-set, N-set, and F-set) of model formation in NASTRAN. Through DMAP alters, the stiffness matrix, and the rigid body modes obtained from the grid point geometry of the structure, are used to calculate the strain energy of the structure at each of the three levels of model formation. The same information is also used to calculate another parameter referred to as the nodal strain to provide further information about modeling problems at each of the levels. As a result, any problems which might be caused by the improper grounding of the structure (i.e., G-set), incorrect application of MPC equations (i.e., N-set), or incorrect definition of the SPC constraints (i.e., F-set) will be identified.

MULTI-LEVEL STRAIN ENERGY CHECK

- IDENTIFIES ILL-CONDITIONING AND CONSTRAINT PROBLEMS AT ALL LEVELS
- APPLIED TO UNCONSTRAINED MODEL
- PROVIDES INFORMATION ABOUT PROBLEMS ASSOCIATED WITH:
  - GROUNDING
  - MPCs
  - SPCs
- IDENTIFIES PROBLEMS ASSOCIATED WITH:
  - G-SET LEVEL
  - N-SET LEVEL
  - F-SET LEVEL
- RIGID FORMAT ALTER IS REQUIRED

METHODOLOGY

The key equations for the Multi-Level Strain Energy Check are shown below. As indicated, two types of matrices, referred to as the nodal strain matrix and the strain energy matrix, are the key elements in identifying modeling errors during each level of model formation (i.e., G-set, N-set, and F-set levels). Examination of these matrices, which are obtained using the rigid body modes (obtained from grid point geometry) and the stiffness matrix at each level (i.e., G-set, N-set, and F-set), will provide information about modeling problems. In the case where there are no modeling errors, the elements of the strain energy matrix at each level should all be zero ideally. Large nonzero values are indicative of modeling errors (this will be discussed in more detail in the following section).

METHODOLOGY

"G" SET CONTAINS ALL DEGREES-OF-FREEDOM
"N" SET CONTAINS ALL INDEPENDENT DEGREES-OF-FREEDOM
"F" SET CONTAINS ALL UNCONSTRAINED DEGREES-OF-FREEDOM

$[\phi_{RB}]$ - **RIGID BODY MODES BASED ON GEOMETRY**
$[K]$ - **STIFFNESS MATRIX**
$[NS]$ - **NODAL STRAIN MATRIX**
$[SE]$ - **STRAIN ENERGY MATRIX**

$$[SE_G]_{6X6} = [\phi_{RB}]^T{}_{6XG}[K]_{GXG}[\phi_{RB}]_{GX6}$$
$$[NS]_{GX6} = [K]_{GXG}[\phi]_{GX6}$$
$$[SE_N]_{6X6} = [\phi^f{}_{RB}]^T{}_{6XN}[K]_{NXN}[\phi_{RB}]_{NX6}$$
$$[SE_F]_{6X6} = [\phi_{RB}]^T{}_{6XF}[K]_{FXF}[\phi_{RB}]_{FX6}$$

$[SE]$ **AT ALL LEVELS SHOULD BE NULL IF STRUCTURE IS UNCONSTRAINED**

NASTRAN IMPLEMENTATION

Implementation of the Multi-Level Strain Energy Check, which is performed by three sets of MSC/NASTRAN DMAP alters, is shown below. These DMAP alters, which are set up for NASTRAN version 65, consist of; 1) calculation of the rigid body modes, 2) calculation of the G-set, N-set and F-set nodal strain and strain energy matrices. In addition, a set of DMAP alters is added which is used to perform the Cholesky Decomposition Check.

The rigid body modes of the structure are first calculated using the grid point geometry data. This is done using the NASTRAN VECPLOT utility module. Next, these modes are partitioned to be used during the N-set and F-set model formation levels. The G-set, N-set, and F-set strain energy matrices (KRBG, KRBN, and KRBF), which are defined in a general form as the product of $\Phi^T K \Phi$, and their corresponding nodal strain matrices (NS), which are defined as product of $K\Phi$, are evaluated. The MATPRN and MATGPR commands are then used to print out each of these matrices. In addition to calculating the nodal strain and strain energy matrices, additional information is also provided by printing the two matrices K_{SS} and K_{FS}. These matrices, which are the result of the application of SPCs to the N-set stiffness matrix, should be null for a model without error. Nonzero terms in these matrices are indicative of problems associated with improper applications of the SPCs.

NASTRAN IMPLEMENTATION

```
                $
                $STRAIN ENERGY AND CHOLESKY DECOMP ALTER
                $
                $ VER. 65; SOL 3
                $
--------------
                ALTER 25
  1ST SET       VECPLOT,   ,BGPDT,EQEXIN,CSTM,,/RBT///4  $
                TRNSP      RBT/RB  $
--------------
                ALTER 124
                VEC        USET/V1/G/M/N  $
                VEC        USET/V2/N/C,N,S/F  $
                PARTN      RB,,V1/,RBNN,,/1  $
                PARTN      RBNN,,V2/,RBFF,,/1  $
                MPYAD      KGG,RB,/G1  $
                MPYAD      RB,G1,/KRBG/1  $
  2ND SET       NORM       G1/G2  $
                MATPRN     KRBG// $
                MATGPR     GPL,USET,SIL,G2//H/G//1.E-2 $
                MPYAD      KNN,RBNN,/N1  $
                MPYAD      RBNN,N1,/KRBN/1  $
                NORM       N1/N2  $
                MATPRN     KRBN// $
                MATGPR     GPL,USET,SIL,N2//H/N//1.E-2 $
--------------
                ALTER 128
                MPYAD      KFF,RBFF,/F1  $
                MPYAD      RBFF,F1,/KRBF/1  $
  3RD SET       NORM       F1/F2  $
                MATPRN     KRBF// $
                MATGPR     GPL,USET,SIL,F2//H/F//1.E-2 $
                MATGPR     GPL,USET,SIL,KSS//C,N,S/C,N,S//1.E-2 $
                MATGPR     GPL,USET,SIL,KFS//F/C,N,S//1.E-2 $
--------------
                DECOMP     KFF/LF,UUAC/V,Y,SYM=-1//S,N,MINDIAG/S,N,DET/
                           S,N,POWER/S,N,SING/S,N,NBRCHG/S,N,MAXRAT $
   CHOLESKY     PARAM      //SUB/V,N,NONPOS/0/NBRCHG $
   DECOMP.      PARAMR     //GT//MAXRAT/1.E+3////V,N,ILL$ COND $
   CHECK        PRTPARM    // $
                DIAGONAL   LF/DLF  $
                MATGPR     GPL,USET,SIL,DLF//H/F  $
                EXIT  $
```

COMMON MODELING ERRORS

Each NASTRAN solution sequence consists of a series of matrix operations which ranges from assembly of the structural matrices to the application of a solution technique for the particular problem of interest. The operations which are of interest to a Multi-Level Strain Energy checkout technique include: (*a*) assembly of the geometric structural matrices, (*b*) application of the multi-point constraint equations, and (*c*) application of the single-point contraints. It is during such operations that modeling problems can occur as a result of incorrect input data.

Common sources of errors which occur during the assembly of the G-set stiffness matrix are due to; (*a*) the improper specification of the coordinate couplings where two components which are located in different coordinate systems are coupled together improperly, (*b*) the use of a short beam element next to a long beam element, (*c*) use of a large or improper aspect ratio for plate elements, or (*d*) the use of CELAS elements between noncoincident points. Each of these modeling practices will result in the ill-conditioning of the G-set stiffness matrix. In the second and third levels of model formation, where the N-set and F-set stiffness matrices are being assembled, improper applications of the MPC equations and SPC constraints could result in further modeling errors. Incorrect specifications of the MPC equations or SPC constraints will result in incorrect representation of the linear relationships among different DOFs and over-constrained boundary conditions, respectively.

COMMON MODELING ERRORS

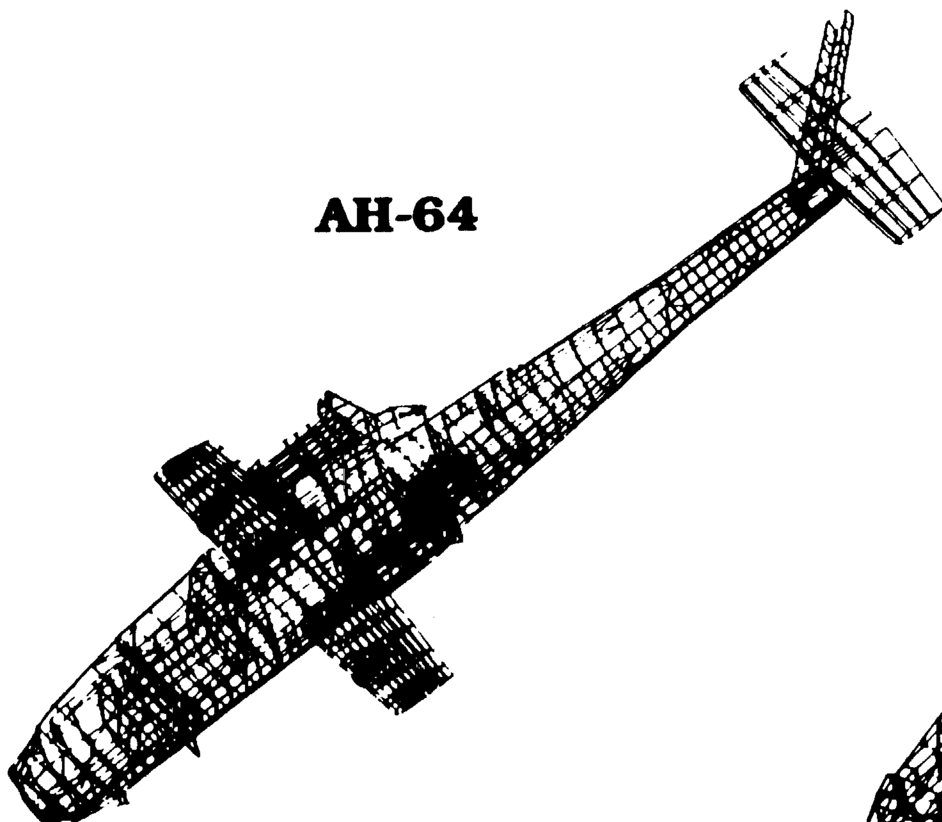
- G-SET LEVEL:
  - IMPROPER SPECIFICATION OF COORDINATE COUPLINGS
  - USING SHORT BEAM ELEMENTS NEXT TO LONG BEAM ELEMENTS
  - USING PLATE ELEMENTS WITH ASPECT RATIOS MUCH HIGHER THAN ONE
  - USING CELAS ELEMENTS BETWEEN NONCOINCIDENT POINTS
- N-SET LEVEL:
  - IMPROPER APPLICATION OF MPC EQUATIONS
- F-SET LEVEL:
  - OVER CONSTRAINTS DUE TO SPCs

APPLICATIONS

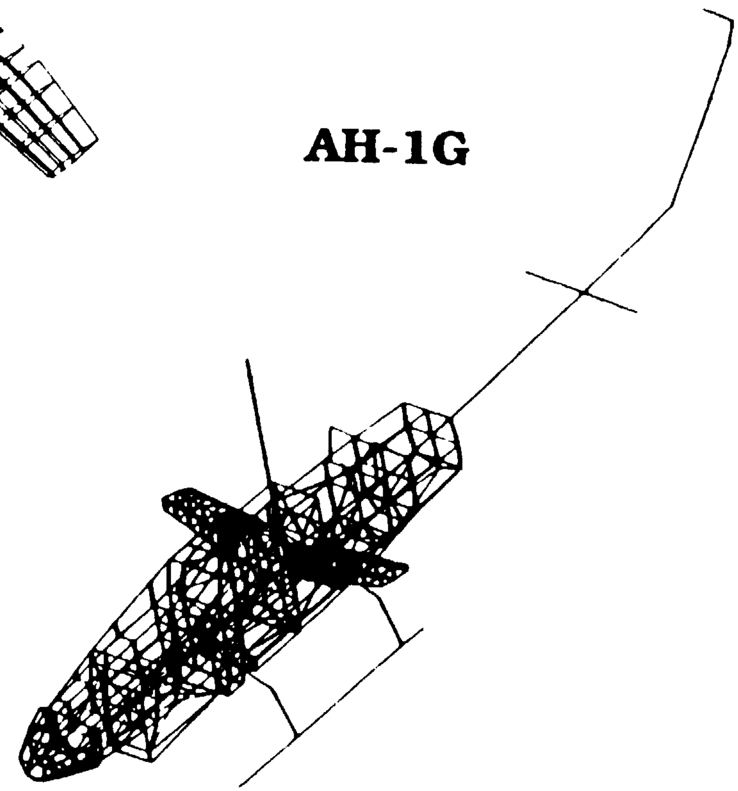
The Multi-Level Strain Energy Check and its associated implementation in MSC/NASTRAN as a set of DMAP alters are illustrated by application to the two airframe finite element models shown in the figure. The first model is the full finite element model of the McDonnell Douglas AH-64 Advanced Attack Helicopter and the second one is the Bell AH-1G helicopter model which was supplied for use in an industry-wide task to calculate the coupled rotor-airframe vibrations of the AH-1G.

APPLICATIONS

AH-64



AH-1G



APPLICATION TO AH-64A NASTRAN MODEL

The AH-64A NASTRAN model is a relatively large model with approximately 1600 grid points, 4000 elements, and a total of 7000 DOFs. For this particular application, only that portion of the model which included the area weapon actuator mount turret was used. The Multi-Level Strain Energy Check was applied to this model under free-free condition and the strain energy and nodal strain matrices were calculated at all three levels. Examination of the G-set strain energy matrix, shown in the following figure, indicates small nonzero values which are due to round-off errors. This matrix, which provides important information about the integrity of the model at the G-set level, indicates no modeling problem. As a result, the G-set nodal strain matrix was not examined. It should be pointed out that for a well-modeled large structure, elements of the strain energy matrix corresponding to the translational DOFs (i.e., first three diagonal elements) typically assume values of less than 10^{-3} whereas for the rotational DOFs (i.e., last three diagonal elements) they typically assume values of less than 10^{+1}.

APPLICATION TO AH-64A NASTRAN MODEL (Continued)

```
                        G-SET STRAIN ENERGY MATRIX

MATRIX KRBG       (GINO NAME 101 ) IS A REAL      6 COLUMN X      6 ROW SQUARE MATRIX.
COLUMN        1          ROWS        1 THRU       6   ------------------------------------
ROW
      1)    -8.1118E-07 -4.3386E-08  3.5881E-09  4.8188E-06 -7.5488E-05 -3.7962E-06
COLUMN        2          ROWS        1 THRU       6   ------------------------------------
ROW
      1)    -5.0277E-08 -9.9349E-07  1.7265E-08  9.0965E-05 -7.0244E-06 -1.0519E-04
COLUMN        3          ROWS        1 THRU       6   ------------------------------------
ROW
      1)     2.0117E-09  1.0125E-08 -9.3412E-07 -2.2842E-07  9.9036E-05  7.2327E-07
COLUMN        4          ROWS        1 THRU       6   ------------------------------------
ROW
      1)     2.8537E-07  5.4299E-05 -3.1333E-06 -4.9422E-03  3.4613E-04  5.7942E-03
COLUMN        5          ROWS        1 THRU       6   ------------------------------------
ROW
      1)    -7.0698E-05  3.3116E-06  1.0174E-04 -9.2951E-06 -1.7358E-02  2.9250E-04
COLUMN        6          ROWS        1 THRU       6   ------------------------------------
ROW
      1)    -5.9730E-07 -8.9586E-05  1.4893E-06  8.0363E-03 -2.2628E-04 -9.6413E-03
THE NUMBER OF NON-ZERO TERMS IN THE DENSEST COLUMN =        6
THE DENSITY OF THIS MATRIX IS 100.00 PERCENT.
```

APPLICATION TO AH-64A NASTRAN MODEL (Continued)

The next step was to study the N-set level strain energy to identify any problems which might be asssociated with the application of the MPC equations. The N-set level strain energy matrix is shown below. A similar examination of this matrix reveals no problem associated with the imposition of the MPCs. Because of the acceptable magnitude of all the terms of the N-set strain energy matrix, examination of the N-set nodal strain matrix was bypassed.

```
                    N-SET STRAIN ENERGY MATRIX

MATRIX KRBN      (GINO NAME 101 ) IS A REAL      6 COLUMN X      6 ROW SQUARE MATRIX.
COLUMN        1         ROWS        1 THRU        6     ------------------------------------
ROW
     1)   -1.0878E-06 -3.7381E-08  4.7345E-07  5.0898E-06 -1.3838E-04 -3.1165E-06
COLUMN        2         ROWS        1 THRU        6     ------------------------------------
ROW
     1)   -9.3306E-08 -1.0822E-06 -2.4144E-08  1.0025E-04 -5.8049E-06 -1.1478E-04
COLUMN        3         ROWS        1 THRU        6     ------------------------------------
ROW
     1)    2.0076E-07 -3.5352E-07 -2.5358E-06  2.3115E-05  2.4524E-04 -3.4402E-05
COLUMN        4         ROWS        1 THRU        6     ------------------------------------
ROW
     1)    3.2111E-06  7.0537E-05 -4.2143E-05 -6.7921E-03  4.7270E-03  7.2895E-03
COLUMN        5         ROWS        1 THRU        6     ------------------------------------
ROW
     1)   -6.0838E-05  2.2347E-05  1.1367E-04  5.4064E-04 -1.3222E-02  1.9443E-03
COLUMN        6         ROWS        1 THRU        6     ------------------------------------
ROW
     1)   -7.1369E-06 -1.3792E-04  2.5450E-05  1.2598E-02 -3.4851E-03 -1.4522E-02
THE NUMBER OF NON-ZERO TERMS IN THE DENSEST COLUMN =        6
THE DENSITY OF THIS MATRIX IS 100.00 PERCENT.
```

APPLICATION TO AH-64A NASTRAN MODEL (Continued)

In the last step, the F-set strain energy matrix shown below was examined. The diagonal terms of this matrix indicate no problems associated with the single point constraints. A comparison of the N-set strain energy matrix with the F-set matrix also showed no differences between the elements of two matrices, which is indicative of the fact that no SPC were applied to this particular component. However, in general this matrix will be different from its N-set counterpart when any single point constraint is applied to the model.

APPLICATION TO AH-64A NASTRAN MODEL (Continued)

```
                        F-SET STRAIN ENERGY MATRIX

MATRIX KRBF      (GINO NAME 101 ) IS A REAL      6 COLUMN X      6 ROW SQUARE MATRIX.
COLUMN       1         ROWS       1 THRU       6     -----------------------------------
ROW
     1)   -1.0878E-06 -3.7381E-08  4.7345E-07  5.0898E-06 -1.3838E-04 -3.1165E-06
COLUMN       2         ROWS       1 THRU       6     -----------------------------------
ROW
     1)   -9.3306E-08 -1.0822E-06 -2.4144E-08  1.0025E-04 -5.8049E-06 -1.1478E-04
COLUMN       3         ROWS       1 THRU       6     -----------------------------------
ROW
     1)    2.0076E-07 -3.5352E-07 -2.5358E-06  2.3115E-05  2.4524E-04 -3.4402E-05
COLUMN       4         ROWS       1 THRU       6     -----------------------------------
ROW
     1)    3.2111E-06  7.0537E-05 -4.2143E-05 -6.7921E-03  4.7270E-03  7.2895E-03
COLUMN       5         ROWS       1 THRU       6     -----------------------------------
ROW
     1)   -6.0838E-05  2.2347E-05  1.1367E-04  5.4064E-04 -1.3222E-02  1.9443E-03
COLUMN       6         ROWS       1 THRU       6     -----------------------------------
ROW
     1)   -7.1369E-06 -1.3792E-04  2.5450E-05  1.2598E-02 -3.4851E-03 -1.4522E-02
THE NUMBER OF NON-ZERO TERMS IN THE DENSEST COLUMN =        6
THE DENSITY OF THIS MATRIX IS 100.00 PERCENT.
```

APPLICATION TO AH-1G NASTRAN MODEL

A second example of the Multi-Level Strain Energy Check was to the Bell AH-1G model. In this particular application, the check was applied to the full model. Examination of the three strain energy matrices revealed some problems at one level (e.g., N-level) of modeling. The Cholesky Decomposition Check was also used and indicated the same problem. Subsequent to identification of the problem areas, steps were taken to correct them.

APPLICATION TO AH-1G NASTRAN MODEL

- APPLIED THE MULTI-LEVEL STRAIN ENERGY CHECK
- APPLIED THE CHOLESKY DECOMPOSITION CHECK
- IDENTIFIED SOME PROBLEM AREAS
- CORRECTED THE PROBLEMS

APPLICATION TO AH-1G NASTRAN MODEL (Continued)

As a part of the normal checkout procedure, both the Cholesky Decomposition and the Multi-Level Strain Energy Checks were applied to the AH-1G model and both approaches revealed problems at the N-set level. Examination of the N-set strain energy matrix (shown below), revealed problems which were associated with the application of the MPC equations. In particular, it is seen that the last three diagonal terms of this matrix are very large. This indicates that there are problems associated with the rotational DOF's. It should be pointed out that while both the Cholesky Decomposition and Multi-Level Strain Energy checks provide the same information, experience has shown that the Multi-Level Strain Energy Check is a better indicator of modeling problems than Cholesky.

N-SET STRAIN ENERGY MATRIX

```
MATRIX KRBN      (GINO NAME 101 ) IS A REAL      6 COLUMN X      6 ROW SQUARE MATRIX.
COLUMN       1        ROWS        1 THRU       6    ----------------------------------
ROW
     1)    -1.1961E-04  1.9650E-07 -5.3704E-08 -2.0193E-05 -9.3913E-03  1.4017E-04
COLUMN       2        ROWS        1 THRU       6    ----------------------------------
ROW
     1)     1.7856E-07 -9.0551E-05  7.0295E-09  6.9417E-03  1.6550E-05 -1.8815E-02
COLUMN       3        ROWS        1 THRU       6    ----------------------------------
ROW
     1)    -9.2082E-09 -1.8501E-08 -3.5235E-05 -9.9218E-05  1.1564E-02 -3.6741E-06
COLUMN       4        ROWS        1 THRU       6    ----------------------------------
ROW
     1)    -9.1880E-06  1.3128E-02 -2.5013E-04  3.0643E+07  2.8283E+03  5.5183E+03
COLUMN       5        ROWS        1 THRU       6    ----------------------------------
ROW
     1)    -2.0488E-02  1.0572E-05  8.5435E-03  2.8282E+03  3.5764E+07 -1.3061E+01
COLUMN       6        ROWS        1 THRU       6    ----------------------------------
ROW
     1)     2.4781E-04 -5.6747E-03 -1.2340E-06  5.5160E+03 -1.3058E+01  8.5029E+04
THE NUMBER OF NON-ZERO TERMS IN THE DENSEST COLUMN =        6
THE DENSITY OF THIS MATRIX IS 100.00 PERCENT.
```

APPLICATION TO AH-1G NASTRAN MODEL (Continued)

The next step was to examine the N-set nodal strain matrix in order to identify the location(s) and the associated DOFs of the troublesome area(s). This matrix, which is of order $(DOFX6)_{N-SET}$, is arranged such that the first three columns correspond to the translations along the X, Y, and Z directions and the last three columns correspond to the rotations about these axes. Prior to printing this matrix, each column of the matrix is normalized such that the largest value in each column is unity. The MATGPR command is then used to print the resulting normalized matrix. By using this command, the normalized N-set nodal strain matrix is filtered in such a way that only terms greater than a certain value (e.g., 10^{-2}) are printed. The table shown below shows the filtered normalized N-set nodal strain matrix. It should be pointed out that only those terms located in columns 4, 5, and 6 need to be examined since the strain energy matrix indicates a problem only with the rotational DOFs (i.e., fourth, fifth and sixth diagonal terms of strain energy matrix have large nonzero values). Therefore, through examination of the terms of the 4th, 5th and 6th columns of the filtered nodal strain matrix it was determined that the rotational terms associated with locations at the turret mount (i.e, grid points 7505 and 15218) have modeling problems. Examination of the model at these locations revealed that several MPC equations were coded incorrectly.

FILTERED NORMALIZED N-SET NODAL STRAIN MATRIX

	POINT	VALUE	POINT	VALUE	POINT	VALUE	POINT	VALUE	POINT	VALUE
COLUMN 1	7505 T1	-1.16577E-02	7505 R2	-2.03491E-01	15212 R2	-1.36719E-02	15218 R2	-1.08643E-02	520024 T1	-3.90625E-02
	520024 R3	-1.07988E-02	520065 T1	-1.25000E-01	520065 R3	1.56250E-02	520068 T1	-1.56250E-02	520135 T1	-3.12500E-02
	520139 T1	-1.56250E-02	18641 T1	-1.52054E-02	18649 T1	-1.48315E-02	18651 T1	-2.53448E-02	18661 T1	-3.43018E-02
	18656 T1	-3.03345E-02	18654 T1	-2.53448E-02	18659 T1	-2.96021E-02	18669 T1	-3.24707E-02	19741 T1	-3.32031E-02
	19751 T1	-5.27344E-02	19749 T1	-3.32031E-02	19759 T1	-5.66406E-02	200078 T1	-5.00000E-01	200078 R2	-1.00000E+00
	200079 T1	-5.42969E-01	200079 R2	3.12500E-02	200095 R2	-2.14844E-02	200096 R2	-3.12500E-02	200153 T1	-1.56250E-02
	200153 R2	-1.56250E-02	21349 T1	-1.95313E-02	21341 T1	-1.95313E-02				
COLUMN 2	7505 R1	1.13085E-01	7505 R3	-1.24775E-02	15212 R1	1.43885E-02	15218 R1	1.75360E-02	30045 T2	-1.03558E-02
	44345 R3	-1.43885E-02	52045 T2	-2.87770E-02	520068 T2	-2.51799E-02	18642 T2	-1.95594E-02	18641 T2	-1.23256E-02
	18648 T2	-1.51754E-02	18649 T2	-1.14891E-02	18652 T2	-1.14799E-02	18662 T2	-1.61871E-02	18651 T2	-1.26411E-02
	18661 T2	-2.74495E-02	18656 T2	-1.03618E-02	18660 T2	-1.07914E-02	18654 T2	-1.44397E-02	18659 T2	-1.04602E-02
	18669 T2	-2.58384E-02	19741 T2	-1.19155E-02	19749 T2	-1.19155E-02	200078 T2	-9.20863E-01	200078 R1	9.20863E-01
	200079 T2	-1.00000E+00	200079 R1	-5.75540E-02	200095 R1	3.95683E-02	200096 R1	5.75540E-02	200112 T2	-1.43885E-02
	200112 R1	1.43885E-02	200153 T2	-2.87770E-02	200153 R1	2.87770E-02	200155 T2	-1.43885E-02	21349 T2	-1.30396E-02
	21341 T2	-1.30396E-02								
COLUMN 3	7505 T3	-1.77612E-02	7505 R1	-1.56250E-02	7505 R2	2.68555E-02	15212 R1	4.68750E-02	19212 R2	-5.46875E-02
	15218 R1	-6.15234E-02	15218 R2	-7.12891E-02	30045 T3	-4.26636E-02	30045 R1	-4.55333E-02	30045 R2	2.62089E-02
	31745 T3	-1.56250E-02	38045 R2	-1.56250E-02	40145 R2	1.56250E-02	44345 T3	-1.56250E-02	44345 R2	6.25000E-02
	45245 R2	-3.12500E-02	52045 T3	-9.76563E-02	520024 T3	-3.12500E-01	520024 R1	1.50391E-01	520057 R1	-3.12500E-02
	520065 T3	-1.00000E+00	520065 R1	-1.25000E-01	520068 T3	-1.25000E-01	520068 R1	3.12500E-02	520079 T3	-1.23291E-02
	520135 T3	-2.50000E-01	520135 R1	-6.25000E-02	520139 T3	-1.25000E-01	520139 R1	3.12500E-02	7043 T3	-1.31531E-02
	8543 T3	-1.17188E-02	14033 T3	-1.46484E-02	14837 T3	-1.56250E-02	18641 T3	-3.71094E-02	18649 T3	-3.32031E-02
	18652 T3	-1.02539E-02	18662 T3	-1.56250E-02	18657 T3	-1.66016E-02	18673 R1	-2.78320E-02	18651 T3	-1.03516E-01
	18661 T3	-7.22656E-02	18656 T3	-7.22656E-02	18668 T3	-1.75781E-02	18658 T3	-1.07422E-02	18677 R1	6.25000E-02
	18654 T3	-8.78906E-02	18659 T3	-8.78906E-02	18669 T3	-5.66406E-02	19761 T3	-5.79987E-02	19752 T3	-1.53809E-02
	19741 T3	-6.13251E-02	19751 T3	-1.15280E-01	19773 R1	1.34277E-02	19758 T3	-1.56250E-02	19769 T3	-5.13611E-02
	19749 T3	-6.18134E-02	19759 T3	-1.56113E-01	200078 T3	-1.25000E-01	200105 R2	-1.56250E-02	194106 T1	2.34375E-02
	194106 T3	-3.12500E-02	200079 T3	-8.59375E-02	200086 T3	-1.56250E-02	200095 T3	-1.56250E-02	200095 R2	-2.18750E-01
	200087 T3	-1.56250E-02	200106 T3	-1.56250E-02	200112 T3	-3.12500E-02	200114 T3	-1.56250E-02	200153 T3	-3.12500E-02
	21383 T3	-1.09863E-02	21361 T3	-1.19171E-02	21377 R1	1.56231E-02	21369 T3	-1.14822E-02	21349 T3	-3.01355E-02
	21341 T3	-3.03345E-02	25049 T3	-1.20544E-02	25069 T3	-1.26256E-02	25041 T3	-1.29395E-02	25061 T3	-1.00403E-02
	26049 T3	-1.01929E-02	26861 T3	-1.05016E-02	26841 T3	-1.09253E-02	62217 T3	-1.39160E-02	72217 T3	-1.39160E-02
	215201 T3	-1.11084E-02	215202 T3	-1.10474E-02						
COLUMN 4	7505 T2	6.53614E-02	7505 R1	-1.00000E+00	7505 R3	1.00243E-01	124800 R1	-4.31329E-02	124800 R2	-1.91342E-02
	7031 T2	-1.48787E-02	7039 T2	-1.48787E-02						
COLUMN 5	7505 T1	-6.51544E-02	7505 R2	-1.00000E+00	7505 R3	1.87233E-02	9333 T1	1.21743E-02	9337 T1	1.17961E-02
COLUMN 6	15212 R1	1.34565E-01	15212 R2	-9.82589E-01	15212 R3	-2.49680E-01	15218 R1	1.37953E-01	15218 R2	1.00000E+00
	15218 R3	-2.57016E-01	124800 T3	-1.60419E-02	124800 R1	-4.95280E-02	124800 R2	1.03571E-01	124800 R3	-1.61768E-01

APPLICATION TO AH-1G NASTRAN MODEL (Continued)

The table shown below represents a portion of the filtered normalized N-set nodal strain matrix shown on page 41. As mentioned previously, rotational DOFs associated with grid point locations 7505 and 15218 have the largest values. Once the associated MPC equation was corrected, the element corresponding to the rotational DOF about the X-axis at the engine support area (i.e., grid 124800) became the largest contributor to this matrix (which is not shown here). This problem was traced back to an MPC equation for the engine support which was improperly written. This equation was then corrected.

APPLICATION TO AH-1G NASTRAN MODEL (Continued)

PORTION OF FILTERED NORMALIZED N-SET NODAL STRAIN MATRIX
ASSOCIATED WITH ROTATIONAL DOFs

COLUMN 4	7505 T2	6.53614E−02	7505 R1	−1.00000E+00	7505 R3	1.00243E−01	124800 R1	−4.31329E−02
	7031 T2	−1.48787E−02	7039 T2	−1.48787E−02	124800 R2	−1.91342E−02		
COLUMN 5	7505 T1	−6.51544E−02	7505 R2	−1.00000E+00	7505 R3	1.87233E−02	9333 T1	1.21743E−02
	9337 T1	1.17961E−02						
COLUMN 6	15212 R1	1.34565E−01	15212 R2	−9.82589E−01	15212 R3	−2.49680E−01	15218 R1	1.37953E−01
	15218 R3	−2.57016E−01	124800 T3	−1.60419E−02	124800 R1	−4.95280E−02	124800 R2	1.03571E−01
	15218 R2	1.00000E+00	124800 R3	−1.61768E−01				

APPLICATION TO AH-1G NASTRAN MODEL (Continued)

Subsequent to the corrections which were made to the MPC equations in both the AH-1G turret mount and engine support locations, the Multi-Level Strain Energy Check was run for the corrected model and the resulting strain energy matrices were compared to those of the original model. The results indicated that the MPC problem was no longer present in the modified model. As an example, the N-set strain energy matrix of the corrected model is shown below. Examination of the elements of this matrix indicates that the magnitude of the rotational terms have been reduced about six orders of magnitude, which is a clear indication of the improvement in the model.

APPLICATION TO AH-1G NASTRAN MODEL (Continued)

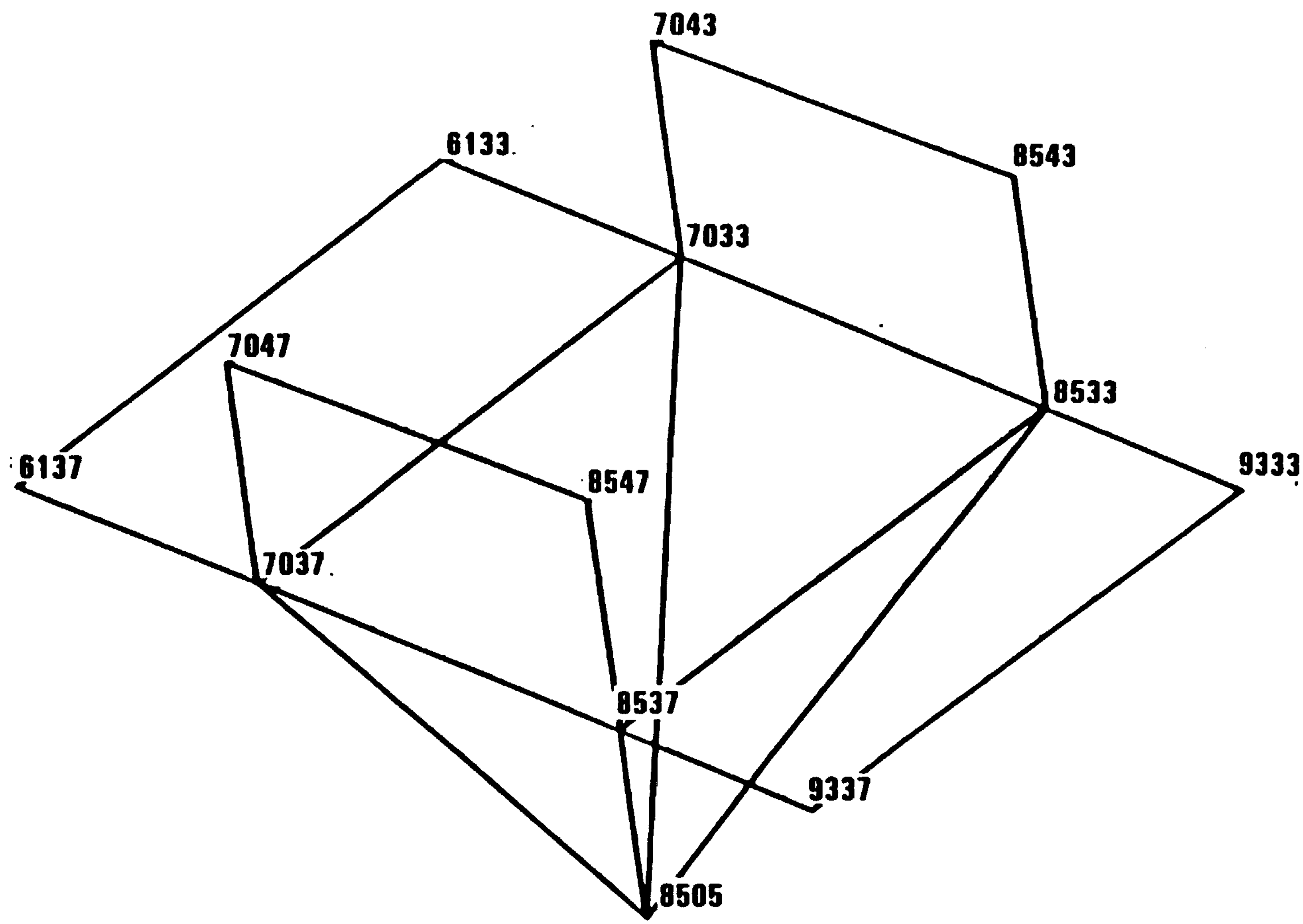
```
                        N-SET STRAIN ENERGY MATRIX

MATRIX KRBN      (GINO NAME 101 ) IS A REAL      6 COLUMN X      6 ROW SQUARE MATRIX.
COLUMN        1          ROWS          1 THRU        6      ------------------------------------
ROW
     1)    -1.1999E-04  1.8256E-07  4.8949E-10 -1.9680E-05 -9.4089E-03  1.4280E-04
COLUMN        2          ROWS          1 THRU        6      ------------------------------------
ROW
     1)     1.7962E-07 -9.0998E-05  1.0765E-08  6.9553E-03  1.6252E-05 -1.8866E-02
COLUMN        3          ROWS          1 THRU        6      ------------------------------------
ROW
     1)     5.4965E-08 -1.3773E-08 -3.5627E-05 -1.0281E-04  1.1636E-02 -3.4798E-06
COLUMN        4          ROWS          1 THRU        6      ------------------------------------
ROW
     1)    -9.3780E-06  1.3161E-02 -2.4993E-04  8.9965E+01  1.2453E-01  2.8377E+00
COLUMN        5          ROWS          1 THRU        6      ------------------------------------
ROW
     1)    -2.0530E-02  7.8777E-06  8.6019E-03  4.0878E-02  7.2995E+01  2.5803E-02
COLUMN        6          ROWS          1 THRU        6      ------------------------------------
ROW
     1)     2.4689E-04 -5.7145E-03 -2.0694E-06  4.5858E-01  2.9161E-02 -1.6473E+00
THE NUMBER OF NON-ZERO TERMS IN THE DENSEST COLUMN =        6
THE DENSITY OF THIS MATRIX IS 100.00 PERCENT.
```

4.0 OTHER EXPERIENCES

AH-1G ILLUSTRATIVE TURRET MOUNT MODEL

As a part of the ongoing effort in improving our finite element modeling capabilities, and in conjunction with the development and application of the above model checkout techniques, some additional studies were made. Subsequent to identifying and correcting the problems associated with modeling of the MPC equations used for the AH-1G turret mount and engine support models, it was decided to examine an alternative means for incorporating the MPC equations. For this purpose, a simplified NASTRAN model of AH-1G turret mount was used wherein the geometry of the model was the same as the AH-1G turret but the corrected MPC equations were replaced by an equivalent RBE2 rigid element. The figure below shows the simplified turret mount model used in this study.

AH-1G ILLUSTRATIVE TURRET MOUNT MODEL



REPLACEMENT OF MPCS WITH AN EQUIVALENT RBE2 RIGID ELEMENT

As a part of this study, the set of the MPC equations was replaced with a single RBE2 element in the simplified model. The following table shows the corresponding MPC and RBE2 inputs for each NASTRAN model. Following the replacement of MPC equations with the RBE2 element, both static and normal mode analyses were performed on the original and modified models. The results obtained from the two models were essentially the same. However, because of the simplicity in use of RBE2 rigid elements, it is recommended that, whenever possible, MPCs be replaced by equivalent RBE2 (or RBAR) rigid elements. The use of such rigid elements is especially useful in situations where the location of the grid points used in an MPC equation may be moved while the MPC equation is not changed.

REPLACEMENT OF MPCS WITH AN EQUIVALENT RBE2 ELEMENT

MPC	1000	7033	1	1.0	7505	1	−1.0	7505FR1
+7505FR1		7505	5	−17.00	7505	6	10.00	
MPC	1000	7033	2	1.0	7505	2	−1.0	7505FR2
+7505FR2		7505	4	17.00	7505	6	4.71	
MPC	1000	7033	3	1.0	7505	3	−1.0	7505FR3
+7505FR3		7505	4	−10.00	7505	5	−4.71	
MPC	1000	7037	1	1.0	7505	1	−1.0	7505FL1
+7505FL1		7505	5	−17.00	7505	6	−10.00	
MPC	1000	7037	2	1.0	7505	2	−1.0	7505FL2
+7505FL2		7505	4	17.00	7505	6	4.71	
MPC	1000	7037	3	1.0	7505	3	−1.0	7505FL3
+7505FL3		7505	4	10.00	7505	5	−4.71	
MPC	1000	8533	1	1.0	7505	1	−1.0	7505AR1
+7505AR1		7505	5	−17.00	7505	6	10.00	
MPC	1000	S533	2	1.0	7505	2	−1.0	7505AR2
+7505AR2		7505	4	17.00	7505	6	−9.76	
MPC	1000	S533	3	1.0	7505	3	−1.0	7505AR3
+7505AR3		7505	4	−10.00	7505	5	9.76	
MPC	1000	8537	1	1.0	7505	1	−1.0	7505AL1
+7505AL1		7505	5	−17.00	7505	6	−10.00	
MPC	1000	8537	2	1.0	7505	2	−1.0	7505AL2
+7505AL2		7505	4	17.00	7505	6	−9.76	
MPC	1000	8537	3	1.0	7505	3	−1.0	7505AL3
+7505AL3		7505	4	10.00	7505	5	9.76	

THIS BLOCK CAN BE REPLACED WITH
RBE2, 900, 7505, 123, 7033, 7037, 8533, 8537

5.0 CONCLUDING REMARKS

CONCLUDING REMARKS

As a result of this work, a procedure has been described which can be used efficiently in identifying modeling errors which may arise in the development of a structural finite element model. This procedure, which is referred to as the Multi-Level Strain Energy Check, is set up in the form of a set of NASTRAN DMAP alters which provide sufficient information about the modeling errors at each of the three levels of model formation (i.e., G-set, N-set, F-set). This technique was applied to two NASTRAN models, namely the McDonnell Douglas AH-64A and the Bell AH-1G models. As a result of the application of this technique to the AH-1G model, two modeling errors were identified. These errors, which were due to improper modeling of the Multi-Point Constraint equations (MPC) at the turret mount and engine support locations, were corrected. An additional study was also performed which examined the use of RBE2 elements in place of the MPC equations. As a result of this study, it is recommended that the RBE2s elements be used instead of MPC equations whenever practical.

CONCLUDING REMARKS

- THE MULTI-LEVEL STRAIN ENERGY CHECK CAN BE USED TO EFFICIENTLY IDENTIFY MODELING ERRORS
- CHECKOUT PROCEDURE IS DEFINED IN TERMS OF DMAP ALTERS
- APPLIED TO TWO HELICOPTER AIRFRAME FEM MODELS
- IDENTIFIED TWO PROBLEMS WITH THE AH-1G MODEL
- PROBLEMS WERE TRACED TO INCORRECT MPC EQUATIONS
- CORRECTIONS WERE MADE AND THE RESULTS WERE VERIFIED WITH THE STRAIN ENERGY CHECK
- RECOMMEND RBE2 OVER MPC WHENEVER PRACTICAL

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15. Supplementary Notes

Langley Technical Monitor: Dr. Raymond G. Kvaternik

16. Abstract

A computational procedure has been described which can be used efficiently in identifying modeling errors which may arise from development of a structural finite element model. The procedure, which is referred to as the multi-level strain energy check, is set up in the form of a set of NASTRAN DMAP alters which provide sufficient information about the modeling errors at G-Set, N-Set, and F-Set levels. This technique was applied to two NASTRAN models, namely, the AH-64A and AH-1G models. Two modeling errors were identified for the AH-1G which were then corrected.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Strain energy, Model Checkout, Finite Element Model, AH-64, AH-1G	Unclassified - Unlimited Subject Category 39

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